51. IWK
Internationales Wissenschaftliches Kolloquium
International Scientific Colloquium

PROCEEDINGS

11-15 September 2006

FACULTY OF ELECTRICAL ENGINEERING
AND INFORMATION SCIENCE

INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING - DEVICES AND SYSTEMS, MATERIALS AND TECHNOLOGIES FOR THE FUTURE

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=12391

TECHNISCHE UNIVERSITÄT
ILMENAU

Impressum

Herausgeber: Der Rektor der Technischen Universität Ilmenau
Univ.-Prof. Dr. rer. nat. habil. Peter Scharff

Redaktion: Referat Marketing und Studentische Angelegenheiten
Andrea Schneider

Fakultät für Elektrotechnik und Informationstechnik
Susanne Jakob
Dipl.-Ing. Helge Drumm

Redaktionsschluss: 07. Juli 2006

Technische Realisierung (CD-Rom-Ausgabe):
Institut für Medientechnik an der TU Ilmenau
Dipl.-Ing. Christian Weigel
Dipl.-Ing. Marco Albrecht
Dipl.-Ing. Helge Drumm

Technische Realisierung (Online-Ausgabe):
Universitätsbibliothek Ilmenau
ilmedia
Postfach 10 05 65
98684 Ilmenau

Verlag:
isle
Verlag ISLE, Betriebsstätte des ISLE e.V.
Werner-von-Siemens-Str. 16
98693 Ilrnenau

© Technische Universität Ilmenau (Thür.) 2006

Diese Publikationen und alle in ihr enthaltenen Beiträge und Abbildungen sind urheberrechtlich geschützt. Mit Ausnahme der gesetzlich zugelassenen Fälle ist eine Verwertung ohne Einwilligung der Redaktion strafbar.

ISBN (Druckausgabe): 3-938843-15-2
ISBN (CD-Rom-Ausgabe): 3-938843-16-0

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=12391

51st Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
September 11 – 15, 2006

R. Stancheva, I.Iatcheva

Effect of End Winding Transposition on the Electromagnetic Field in a Turbo-generator

INTRODUCTION

The stator core winding in power turbo-generators has rather large rated electric current up to several thousands amperes. Of course it is preferable the windings to be made of sections composed of up to thirty conductors connected in parallel. To reduce the circulating currents induced in the conductors and the dissipative losses the conductors should be transposed at different positions [1, 2]. For example the transposition begins from the top to the bottom of the slot and the conductors change their situations choosing available positions in the end windings. The difficulties are due not only to evaluate the circulating currents when are known the real positions of the conductors [3] in design but especially to define the optimal design transpositions [4]. This paper considers the first investigation step. It presents a method for non compensated electromotive voltages and circulating currents evaluation applying FEM for the field analysis. The second step including optimal transposition design for stator core slots and end windings of power turbo-generator (TG) will be discuss later. The multi-section scheme of the stator winding is used. The magnetic field-electric circuit coupled analysis is made for circulating currents determination. The method takes into account the demagnetized effect due to these currents. The complex electromagnetic power incoming to the transposed winding is numerically evaluated on the basis of the Pointing vector. As a result the displacement current and its coefficients, and the conductor number p complex impedance are calculated. The general theoretical electromagnetic field model [5] allows making the following valuations:

1. Transposition influence on electromagnetic field in the end region of TG;
2. Non-compensated electromotive forces and circulating currents in the presence of transposition.

An application example is given, referring to the 200MW generator.

A SHORT REVIEW OF ELECTROMAGNETIC FIELD MODEL

Axial section of the 200MW turbine-generator end region is shown in Fig.1.

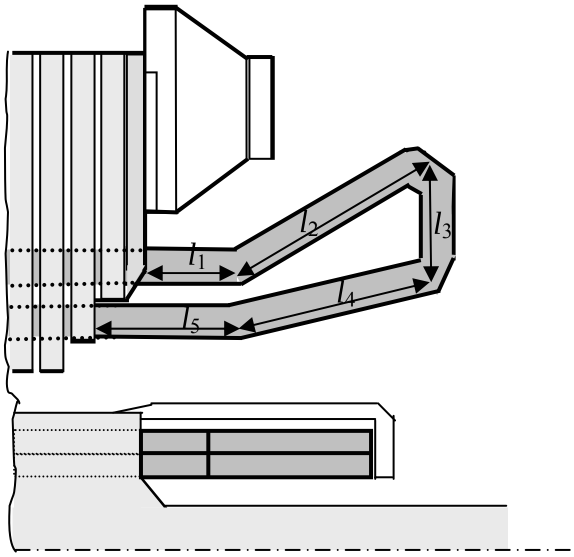

Fig.1. Axial section and end winding of 200MW turbine-generator

The electromagnetic field is analyzed as quasi-three-dimensional and time-harmonic taking into account the actual currents of the three-phase stator and rotor windings, anisotropy in the tooth zone, eddy currents in the conductive media and the generator state (load angle and power factor). The describing equations are:

$$\mathrm{rot}(\hat{\nu}\,\mathrm{rot}\,\vec{A}) = \hat{\sigma}\vec{E} + \vec{J}_e \tag{1}$$

$$\vec{E} = -\mathrm{grad}\,V - \frac{\partial \vec{A}}{\partial t}. \tag{2}$$

Vector $\vec{A}$ is the magnetic vector potential, $\vec{E}$ is the electric field intensity, V is the scalar electric potential, $\hat{\nu}$ and $\hat{\sigma}$ are tensors due to the magnetic reluctivity and electric conductivity of the anisotropic medium. The specific electric losses in unit volume of the conductors are due to the current density $\dot{\vec{J}}$ taking into account Joule's low as follows:

$$p_c = \frac{[\sigma]^{-1}\vec{J}.\dot{\vec{J}}}{2}. \tag{3}$$

METHOD DESCRIPTION
Multi-section scheme

To simulate the magnetic field within and around the slots and end windings accurately the transposed locations of each conductor are based on the positions of sustaining sections in the stator core part of the winding and in outstanding parts of it. Between two sustaining sections the change of the positions is possible. These sections divide the winding into several longitudinal parts which depend on the chosen model of transposition. In the present paper preferable model of transposition proposed in perspective TG is considered. It is conventionally denoted as scheme $-\frac{1}{2}\times 360/540/\frac{1}{2}\times 360$ and is shown in Fig.2. In this case so-called bi-flux scheme of transposition is used.

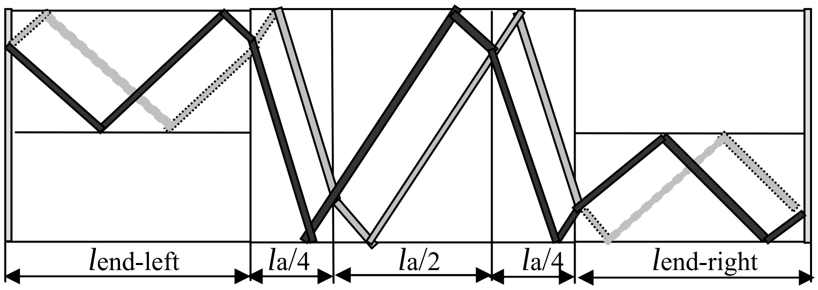

Fig.2. Preferable model of transposition- scheme $-\frac{1}{2}\times 360/540/\frac{1}{2}\times 360$

Conductors are on 540 degree intertwine in the slots and in the end winding they form two-top and bottom layers where intertwinement is made on 360 degree. Transposition of 540 degree means that each elementary conductor passes two times from one vertical row to the other. At the entry and the exit of the slot it is situated at different vertical rows and gradually changes its position along the height of the slot similarly the spiral. The conductor offset and its end are in different radial layers. In Fig. 2 outgoing from the slot elementary conductors are shown by the bold line-if they are rising and by light line-when they are descending. In end winding transposition the rising elementary conductor at the left end winding is suitable to the descending elementary conductor at the right end winding and vice versa. The transposition is made at only 80% of the whole end winding length (10% is part from the stator core end to the winding bending and the rest 10% is needed for elementary conductors solder). The change of elementary conductors positions first hand outside the stator core as well as the influence of the real stator core skewing over the non compensated electromotive forces and circulating currents has been considered. Investigation has been made for 16 elementary conductors connected in double row parallel in the coil. So the number of elementary conductors in the row is $\frac{m}{2}=8$. Dimension of one conductor along the height h_1 of the slot is than h_1/m. At the issue ($z'=0$) of stator core the distance y'_{bp} of the serial number p, with $p = 1,2,..,\frac{m}{2}$, elementary conductor axis to the bottom of the slot (Fig.3) is presented by relative coordinate $k_p = \frac{1}{2m}(2p-1)$ accepting $k = \frac{y_b^{'}}{h_1}$. The relative variable changes from $k = \frac{1}{2m}$ to $k = 0.5 - \frac{1}{2m}$. Points where elementary conductors are bended along the end winding could be marked by: $z_1^{'} = kl$; $z_2^{'} = (0.5+k)l$; $z_3^{'} = (0.5-k)l$ and $z_4^{'} = (1-k)l$. The descriptions made above refer to the geometry and geometrical parameters determining the way of transposition in the end winding.

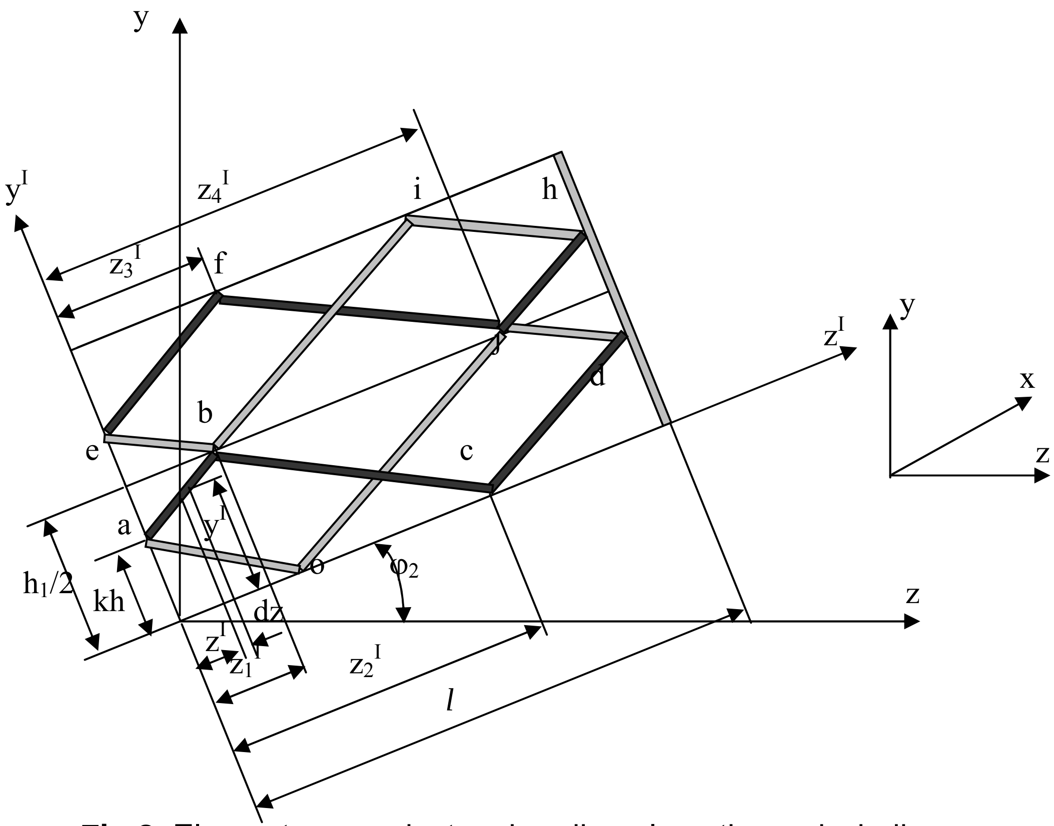

Fig.3. Elementary conductors bending along the end winding

Transposition influence on magnetic field

Since end winding cross section is densely occupied by the two rows elementary parallel conductors it follows that to the part dz, respectively $dz^{'}$, of one arbitrary elementary conductor a similar (removed parallel to the x axis) conductor corresponds. It belongs to the other vertical row. Thus overlapping in region $dz^{'}$ one rising (1) and the relevant descending (2) conductors are considered in Fig.4.

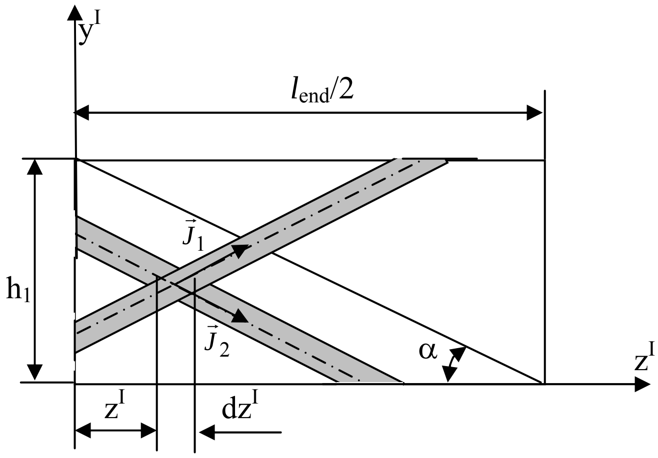

Fig.4. Overlapping conductors from two vertical rows of end winding

Sum between current density vectors: $\mathbf{J}_1$ and $\mathbf{J}_2$ crossing elementary conductors 1 and 2 respectively gives as a result:

$$\mathbf{J}_1 + \mathbf{J}_2 = (J_{1z'^1} + J_{2z^1})\mathbf{z}'^0 = 2J_e \cos\alpha\, \mathbf{z}'^0 , \tag{4}$$

where $\alpha = arc\,tg\frac{h_1}{2l}$ because of the two layers winding. In the last expression $l = 0.8(l_1 + l_2)$ and $l = 0.8(l_4 + l_5)$ denotes the length of the top and the bottom winding layer. Thus the resulting current density is obtained multiplying current density of the exciting current J_e by the correction coefficient $\cos\alpha$. Taking into account that in 200 MW turbine-generators the following dimensions are valid: $h_1 = 20.5\,\text{cm}$ and $l_2 + l_4 = 162\,\text{cm}$ the multiplier is $\cos\alpha = 0.992$. Diminution of the exciting current is under 0.8% and because of the linearity of investigated region it follows that at the same rate magnetic flux density amplitude will decrease.

Algorithm for electric field calculation in elementary conductors

Investigation has been made of the end winding field supposing that magnetic vector potential $\mathbf{A}$ and magnetic flux density $\mathbf{B}$ are known.

1. Cycle, number of which depends on the type of transposition, begins;
2. For the two layer winding l is determined;
3. Number p of the elementary conductor is changed: $p = 1,2,...,\frac{m}{2}$ (for two layer winding). The relative coordinate k_p is calculated;
4. Different parts (sections) of the transposing end winding are considered. Their geometrical parameters are determined taking into account the number of the

layer and the coordinates z' of the relevant section. Numbers i and j of finite element row and column, respectively, are specified in the region.

5. Magnetic vector potentials are calculated. Field model [5] is supposed quasi-three dimensional. The three special components of the magnetic field are accounted for. The field values are determined in one axial section of the machine considering the region of the end windings. For example under the sinusoidal excitation the governing equations in Cartesian coordinates in this region are

$$\begin{aligned}
&\frac{1}{\mu}\frac{\partial^2 \dot{A}_x}{\partial y^2}+\frac{1}{\mu}\frac{\partial^2 \dot{A}_x}{\partial z^2}-\frac{1}{\mu}\frac{\pi^2}{\tau^2}\dot{A}_x - j\omega\sigma\,\dot{A}_x = -\dot{J}_{ex},\\
&\frac{1}{\mu}\frac{\partial^2 \dot{A}_y}{\partial y^2}+\frac{1}{\mu}\frac{\partial^2 \dot{A}_y}{\partial z^2}-\frac{1}{\mu}\frac{\pi^2}{\tau^2}\dot{A}_y - j\omega\sigma\,\dot{A}_y = -\dot{J}_{ey},\\
&\frac{1}{\mu}\frac{\partial^2 \dot{A}_z}{\partial y^2}+\frac{1}{\mu}\frac{\partial^2 \dot{A}_z}{\partial z^2}-\frac{1}{\mu}\frac{\pi^2}{\tau^2}\dot{A}_z - j\omega\sigma\,\dot{A}_z = -\dot{J}_{ez}.
\end{aligned} \tag{5}$$

The current density components in (5) depend on the position of the exciting current density (Fig.3). The amplitude of the current density is determined for elementary conductor number p by the expression $J_e = \frac{I_p}{S_p}$, for $p = 1,2,...,\frac{m}{2}$, where S_p is cross section of number p elementary conductor. These values are the same for the top and the bottom layer of the winding. The electric circuit equations are given by the terms

$$\dot{I}_p Z_p - \dot{E}_p = \dot{U} \qquad \text{for} \quad p = 1,2,...,\frac{m}{2}. \tag{6}$$

Here by $\dot{U}$ and Z_p the outlet voltage of the stator winding and complex impedance of number p elementary conductor are respectively denoted.

6. Complex impedance Z_p of number p elementary conductor is determined taking into account the displacement current effect.The complex electromagnetic power outgoing from transposed winding is numerically evaluated on the basis of the Pointing vector. Knowing the field values the conductor number p complex impedance is calculated by the expression

$$Z_p = \frac{1}{I^2}\frac{j\omega}{\mu_0}\sum_{r=1}^{R}\sum_{e_p=1}^{m}\iint_{(\Delta_{ep})}[\dot{A}_y\frac{\partial \overset{*}{\dot{A}}_x}{\partial y}+\dot{A}_z\frac{\partial \overset{*}{\dot{A}}_x}{\partial z}-\frac{\pi}{\tau}ctg(\frac{\pi x}{\tau}-\varphi)(A_y^2+A_z^2)]dydz\,\cdot \tag{7}$$

On the basis of equation (7) the term for resistance R_p of number p elementary conductor is brought out

$$R_p = \frac{1}{I^2}\frac{\omega}{\mu_0}\sum_{r=1}^{R}\sum_{e_p=1}^{m}\iint_{(\Delta_{ep})} \mathrm{Im}[\dot{A}_y \frac{\partial \overset{*}{\dot{A}}_x}{\partial y} + \dot{A}_z \frac{\partial \overset{*}{\dot{A}}_x}{\partial z}]dydz. \tag{8}$$

7. Induced electric voltage $\dot{E}_p$ is calculated applying equation

$$\begin{aligned}\dot{E}_p &= -\frac{\partial \psi_p}{\partial t} = -j\omega \oint_{(\Gamma)} \dot{\mathbf{A}}_p.\mathbf{dl} = -j\omega \sum_i \sum_j [\Delta y' \int_{\Delta z'} A_{z'i,j}dz' + \Delta z' \int_{\Delta y'} A_{y'i,j}dy'] = \\ &= \frac{-j\omega}{3}\sum_{r=1}^{R}\sum_{e_p=1}^{m}\{\Delta_{e_p}[(A_{zk}+A_{zq}+A_{zt})+(A_{yk}+A_{yq}+A_{yt})]\}.\end{aligned} \tag{9}$$

Quantities used in the expression above are symbolized by: Δ_{e_p} -the area of element e_p; A_{zk}, A_{zq}, A_{zt} and A_{yk}, A_{yq}, A_{yt} are z and y -components, respectively at three nodes k, q and t of element e_p; R is number of the end winding sections in the presence of transposition. Equations (9) are solved for the left and the right parts of end windings at once considering the conditions imposed by multi-section scheme.

8. Replacing (7) and (8) in (6) so obtained system of field-circuit coupled equations is solved with the relevant boundary conditions by using FEM. As a result the currents $\dot{I}_p$ in transposed parallel conductors are calculated. Then using (9) electromotive forces $\dot{E}_p$ in these conductors are also determined.
9. Provided that transposition is approximately effective it is possible to introduce equality $Z_1 = Z_2 = ... = Z_p = ... = Z_{\frac{m}{2}} = Z$. Than equivalent electromotive force $\dot{E}_{eq}$ of the whole winding bar is defined as the middle one

$$\dot{E}_{eq} = \frac{2\sum_{p=1}^{m/2}\dot{E}_p}{m}. \tag{10}$$

Then the relative value of non compensated electromotive force is determined by the expression

$$e_p = \frac{0.5m\left|\dot{E}_p\right| - \left|\sum_{p=1}^{m/2}\dot{E}_p\right|}{\left|\sum_{p=1}^{m/2}\dot{E}_p\right|}. \tag{11}$$

CALCULATION RESULTS

Electromagnetic field analysis

The three components of the complex magnetic vector potential $\dot{A}_x, \dot{A}_y, \dot{A}_z$ and electric scalar potential $\dot{V}$ have been calculated. Investigation of the magnetic flux distribution for the three components $\dot{B}_x, \dot{B}_y$ and $\dot{B}_z$ has been also carried out.

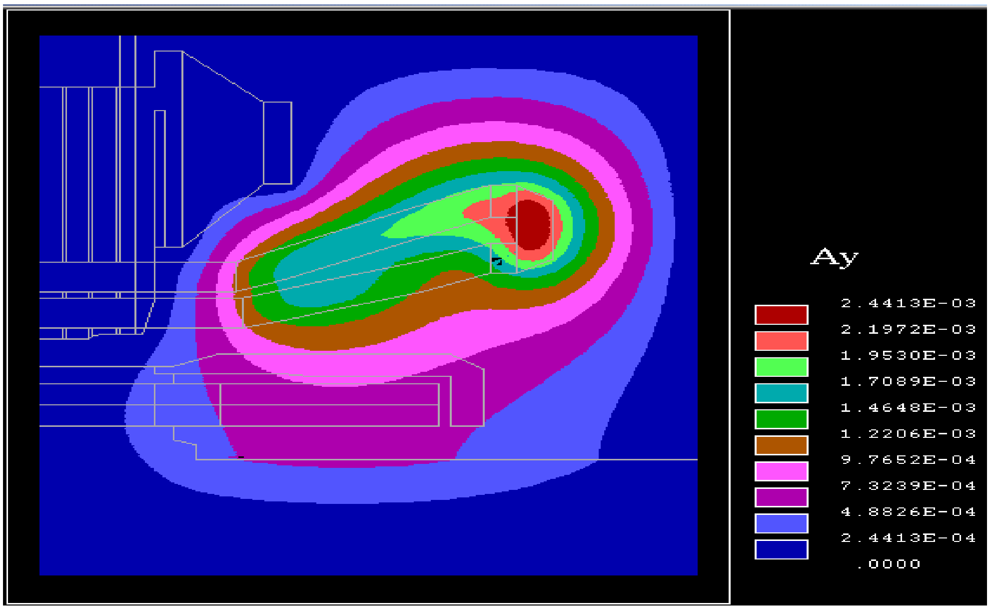

Fig.5. Component $\dot{A}_y$ of magnetic vector potential

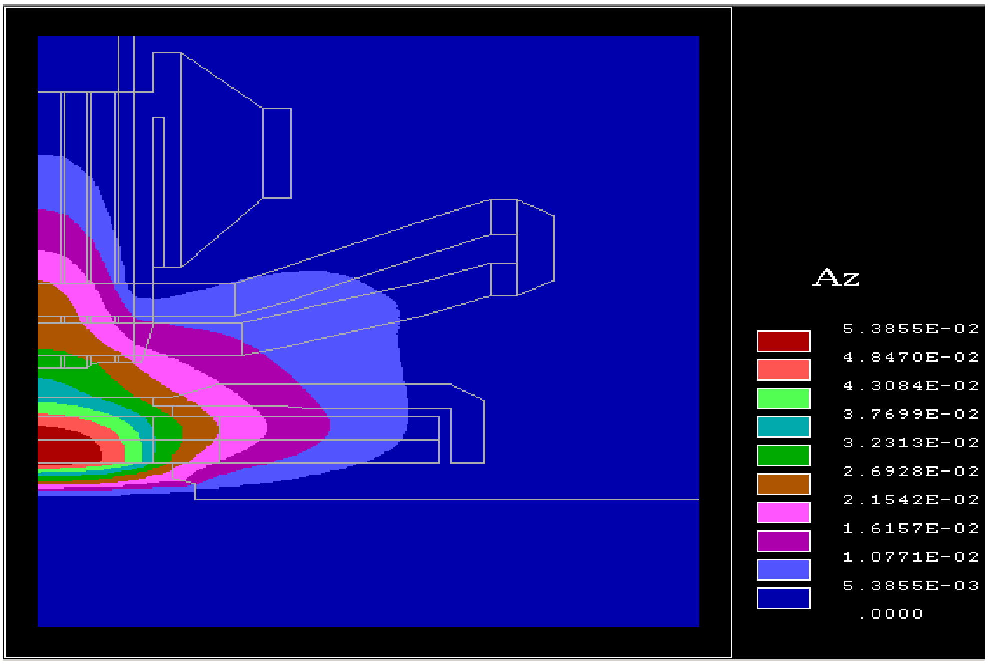

Fig.6. Component $\dot{A}_z$ of magnetic vector potential

Obviously transposition effects depend mainly on $\dot{A}_y$ (Fig.5) and $\dot{A}_z$ (Fig.6) component of the magnetic vector potential and on the tangential component $\dot{B}_x$ (Fig.7) of the magnetic flux density. Because of this fact special attention was paid to their distribution in the region of stator end zone as was shown in the mentioned figures.

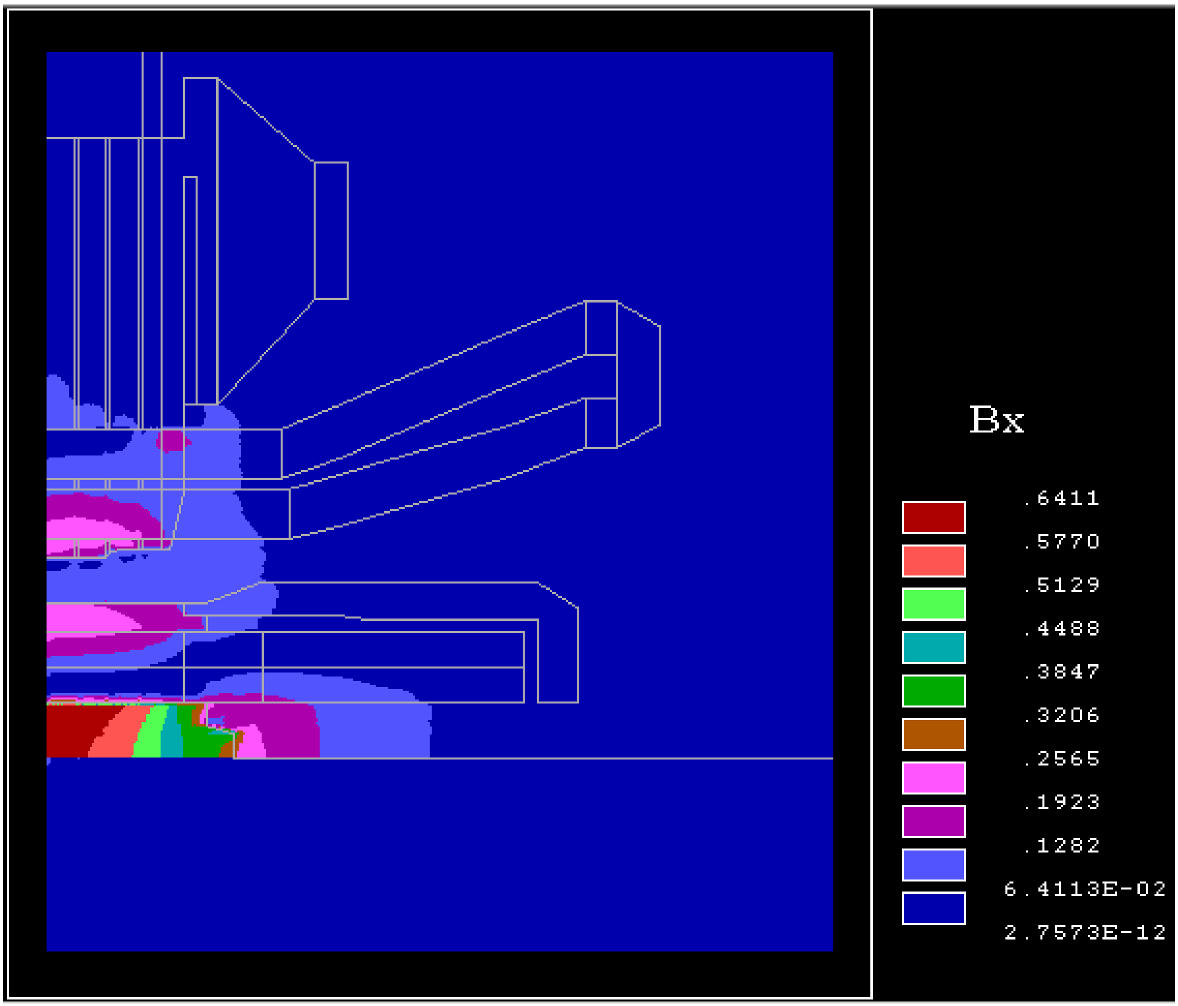

Fig.7. Component $\dot{B}_x$ of magnetic flux density

Applying algorithm described above non-compensated electromotive forces e_p are calculated in relative units. The graphics are shown in: Fig.8- e_p change along the height of the bottom bar; Fig.9- e_p change along the height of the top bar and in Fig.10- e_p curve along the height of the slot. From the bottom to the top of the slot radial dimension is changed from 0.63 to 0.80m.

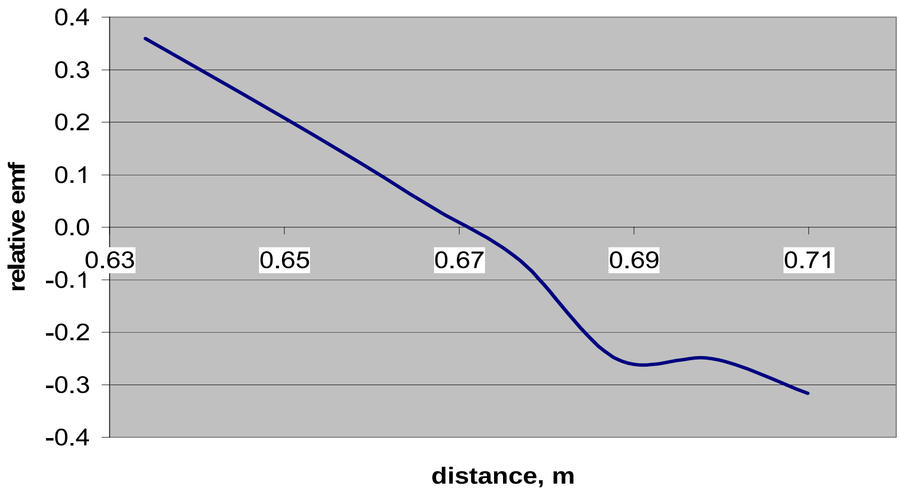

Fig.8. Non-compensated emf e_p in relative units along the height of the bottom bar

Fig.9. Non-compensated emf e_p in relative units along the height of the top bar

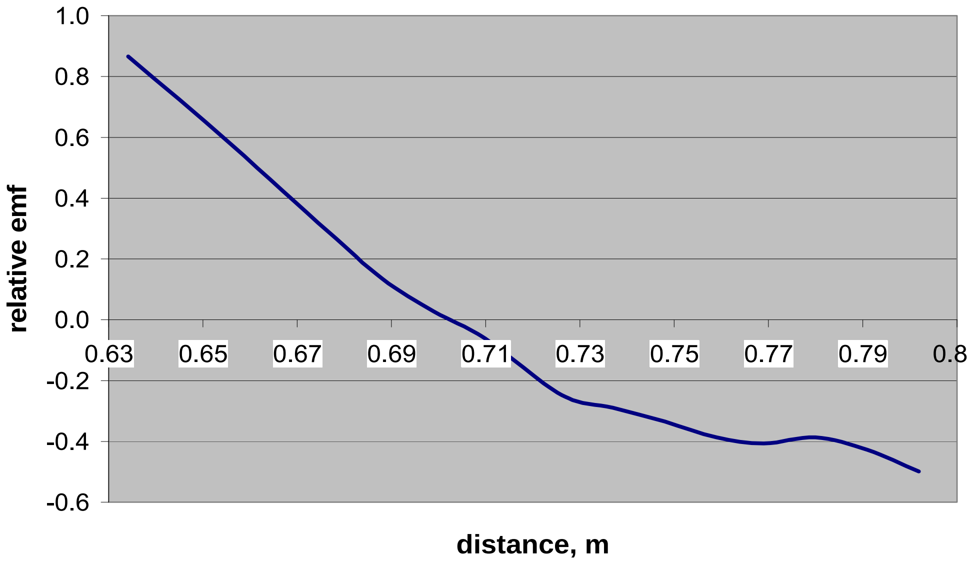

Fig.10. Non-compensated emf e_p in relative units along the height of the slot

If someone accepted that circulating currents depend only on ohmic resistance of the conductors then in different scale these curves could present the circulating current changes.

Results show that values of non-compensated emf in the bottom bare are approximately two times bigger than in the top bar. The reason is due to the stator core end skewing. Electromotive force changes sign keeping its absolute value in two directions.

CONCLUSIONS

On the basis of magnetic field-electric circuit coupled analysis electromagnetic field is calculated in a longitudinal section of turbogenerator in the presence of conductor's transposition. Electric field in the elementary transposed conductors is evaluated. Calculations are executed on the basis of the proposed algorithm. Example is referring to 200MW turbine generator.

Influence of the exciting currents over produced magnetic field decreases because of the transposition. Diminution of the exciting current is up to 0.8%. Taking into account the linearity of investigated region it follows that at the same rate amplitude of magnetic flux density decreases.

Non-compensated electromotive forces in transposed elementary conductors are calculated in relative units. Graphics are presented in relative units for electromotive forces and in different scale they are also valid for circulating currents.

The results show that because of the stator core end skewing the values of non-compensated emf in the bottom bare are approximately two times bigger than in the top bar. Electromotive force changes it sign keeping its absolute value in two directions.

References:

[1] X. Dexin, Y.Hiuke,Y.Yingying, B.Baodong and N.Takahashi: "Circulating current computation and transposition design for large current winding of transformer with multi-section strategy and hybrid optimal method", IEEE Trans. on Magnetics, vol. 36, 2000, pp.1009-1014.

[2] Ю.А. Бобков: "Исследование эффективности транспозиции проводников в лобовой части стержня статорной обмотки турбогенератора", Техн.электродинамика, №2, 1989.

[3] Ю.А. Бобков: "Определение некомпенсированной разности э.д.с. в проводниках обмотки статора при большом скосе концевых пакетов сердечника турбогенератора", Электротехника, №11, 1986, с. 21-23.

[4] B.Baodong, X. Dexin, C.Jiefan and F.Zhenyao: "Optimal transposition design of transformer windings by genetic algorithms", IEEE Trans. on Magnetics, vol. 31, 1995, pp.3572-3574.

[5] R.Stancheva and I.Iatcheva: "Numerical determination of operating chart of large turbine generator", Int. Conf.on Electr. Machines ICEM'2002, Belgium, Book of Abstr. pp.329, Full text on CD.

[6] I.Ziari and A.Valedi: "Identification of three phase induction motor parameters using average charge response of stator currents", Intern. Aegean Conference on Electrical Machines and Power Electronics, Turkey, 2004, pp. 272-278.

Authors:

Assoc. Prof. PhD. Rumena Stancheva, Assoc. Prof. Dr. Ilona Iatcheva
Technical University of Sofia, 8, Kl. Ohridski Blvd
1000 Sofia, Bulgaria
Phone: +359 2 965 3389
Fax: +359 2 68 32 15
E-mail: rds@vmei.acad.bg, iiach@tu-sofia.bg